HEATING OF AIR BY SOLAR ENERGY

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In the application of solar energy to the heating of dwellings and other uses, the primary element in the heating system is the solar collector. The function of the collector is the converting of solar radiation falling on its surface to energy in the form of sensible or latent heat in a fluid which is passed through the collecting unit.

Numerous types of solar energy collectors have been devised. The focusing type, (Muchot, 1879), employing lenses or mirrors to concentrate the solar energy onto a small, high-temperature area has been built in a variety of forms. The initial cost of this equipment appears at this time to preclude its practical use in house heating or power generation applications. Of considerably greater interest from the standpoint of economic practicability, are the several types of flat-plate solar collectors in which a fluid is heated by contact with surfaces which are heated in turn by solar radiation passing through one or more flat glass surfaces. These stationary units, vertical or sloping, have been experimentally studied in several laboratories and demonstration house installations by a number of investigators, (Hottel and Woertz, 1942; Telkes, 1950). The studies on which this paper is based have involved a solar heat collector of a stationary, sloping, flat-plate type, in which ordinary, single-strength window glass is employed both as a heat exchange surface and as an "insulating medium," which reduces escape of heat to the atmosphere.

The purpose of the collector unit employed in this development is the heating of air by passing it between overlapped glass plates and delivering the heated air to a dwelling, or to a heat-storage unit, or, in the case of air-conditioning application, to the air-conditioning unit. Associated with this purpose has been the objective of developing a permanent solar collector of minimum fixed and operating cost and pleasing appearance.

Although not the subject of this paper, several other closely related phases of the development program have been:

(1) Fundamental study of heat transfer coefficients between air and heated flat plates.
(2) Heat transfer characteristics and performance of a heat storage bed of 1-inch gravel.
(3) Performance characteristics of a solar collector of optimum design.
(4) Performance of a solar collector at temperatures suitable for air-conditioning application.
(5) Performance of a dehumidification-type air conditioner.
(6) Design and predicted heating costs for solar heated houses in Denver, Colorado and Dallas, Texas.

This paper deals with the studies associated with the performance of the most efficient form of the solar collector under winter heating conditions. Primary objectives have been the determination of the relationships between useful heat recovery, solar intensity, outdoor ambient air temperatures, type and arrangement of glass plates in the unit.

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DESCRIPTION OF APPARATUS

In order that the function and arrangement of the collector may be more clearly evident, the general arrangement of the complete solar heating system in a dwelling may be outlined. The collector unit of suitable area is located in the roof of the dwelling, flush with the roofing surface; air circulated up the sloping collector between its glass surfaces, enters a manifold at the collector exit, passes to a fan, and then either to the rooms of the dwelling or into the top of a vertical storage bin of 1-inch to 1½-inch gravel. If the air is being directed to the rooms of the house by the thermostatic controls, it finally leaves them via the cold air return and passes through ducts to the collector inlet. If, however, heat is being stored, the air after delivering its sensible heat to the gravel bed, leaves the bottom of the bin and returns through a duct to the collector inlet. Finally, when the house requires heat at night, air is drawn from the rooms through the cold air return duct to the bottom of the storage bin, is heated by its passage through the gravel, and is forced by the blower through the heating duct to the rooms. An auxiliary duct heater is incorporated in the system for use when solar heat is not available.

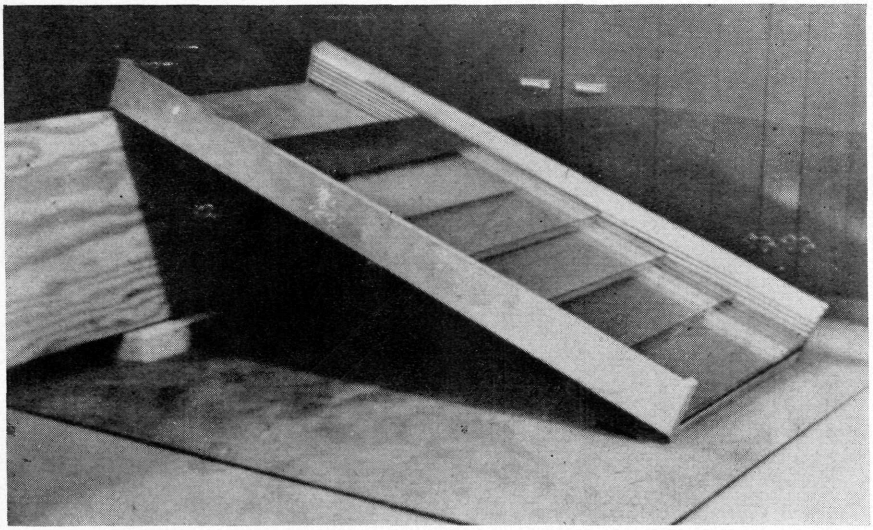

FIGURE 1. A solar collector.

The solar collector, as presently developed, consists of a multiple of individual units 2 ft. × 4 ft. in size. A series of four such units, each comprising a thin sheet-metal trough approximately four inches deep and an arrangement of glass plates, is shown in figure 1.

The basic heat-recovery element in the unit consists of a pane of single strength window glass 2 ft. × 18 in. coated with a black heat absorbing surface the entire two feet width of the plate for a distance of six inches along the 18-inch length. A number of these plates supported at their edges by one of several arrangements is installed in the unit, black surfaces uppermost, and overlapped so that each black surface is beneath two clear surfaces. In the presently-employed construction, spaces of one-fourth inch are provided between successive plates. At the two ends of the unit, 6-inch and 12-inch plates are installed so that a uniform exposure of black plates is obtained. Above the entire series of overlapped plates, and resting on the top edges of the trough, a single sheet of glass 2 ft. × 4 ft. in size is supported. In some trials, two and three such cover plates were employed.

The heat absorbing surface presently employed is a dull surface of black glass fused to the surface of the pane.

The basic principle of the overlapping plate arrangement with the theory of of its function was first described by Miller (1943), and is similar to the "greenhouse effect". This effect depends upon the fact that glass is transparent to visible and short infrared wavelengths which make up the predominate portion of sunlight and is opaque to long infrared wavelengths such as originate in black bodies below 500° F. When the sunlight enters a glass-covered enclosure, it impinges on the contents, is absorbed, thereby heating the interior surfaces which then emit low temperature, long wavelength radiation which is trapped inside the glass enclosure. Thus, when the collector is exposed to solar radiation, the black surface will become heated to an elevated temperature which may be in the vicinity of 300° F. This surface will radiate to the clear surface above and heat it to some lower temperature, such as 200° F. This surface will in turn heat the one above it to still a lower temperature—say 100° F. and finally that surface will heat the cover plate to a temperature a few degrees above the surrounding atmosphere. Because of symmetry

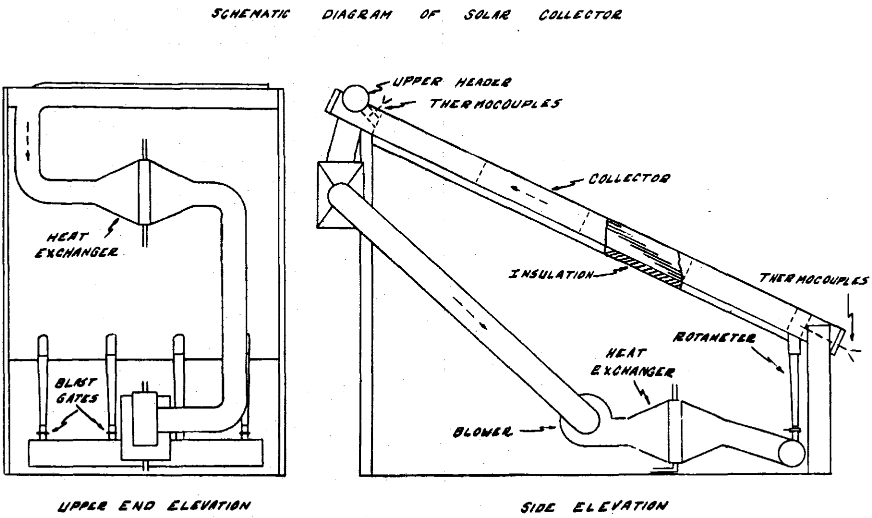

FIGURE 2. Schematic diagram of a solar collector.

in the unit, this vertical temperature gradient is duplicated along a single plate; thus, the air passing between two adjacent plates encounters a progressively rising temperature until it leaves the end of the black surface at the maximum temperature.

The low air velocity employed (about 1 ft./sec.) introduces very little turbulence between plates, thereby causing little convection loss from plate to plate. Hence, the principle factors contributing to the loss of heat from the unit are the plate-to-plate radiant transfer described above, and essentially pure heat conduction through the streamline air layers and glass plates. By the arrangement of black and clear glass areas, it is therefore possible to heat air to a temperature closely approaching that of the black surface.

The complete experimental collector employed for the studies of performance is diagrammed in figure 2. The collector, mounted on a 27° south slope, consists of sixteen individual 2 ft.×4 ft. troughs. These are arranged in four rows of four units each. Two finned-tube heat exchangers are provided in the air circuit for air temperature control. A blower of the flat-blade centrifugal type is used for air circulation.

The individual collector units are supported at their top edges and sides by wooden rafters. Glass-wool insulation is provided beneath the collector troughs and on all air ducts.

In most of the tests, each of the four rows was provided with a different cover plate arrangement. In two of the troughs, ordinary single strength glass was used, one was provided with single cover plates, the other with double cover plates separated by a ¼-inch air space. In the other two troughs, surface-treated glass was used throughout; single covers were used on one, double on the other. The treatment of the glass involved the formation of a surface film of silica, one-fourth wavelength in thickness. This etching process, developed by RCA (Nicall, 1942) for reducing surface reflection, was found to be highly satisfactory.

Instrumentation consisted of four rotameters, one in each of the four rows; thermocouples were installed at the inlet in each row and at the exit connector duct leading from the upper end of each trough into the hot manifold. Gate valves were provided at the rotameter inlet for control of the air circulation rate.

Apparatus other than that employed in the collector system itself consisted of an Eppley ten-junction pyrheliometer for measurement of solar energy input at a 27° angle, a Leeds and Northrup Recorder for this instrument, and a 12-point recorder for temperatures throughout the unit.

EXPERIMENTAL PROCEDURE

The studies performed with the present collector arrangements may be divided into two phases, those involving winter operation with house heating application, and those in which air was recirculated through the unit at moderate or high temperatures in order that performance under conditions required for air conditioning could be obtained. Although similar operating procedures were employed in these two types of tests, the detailed steps differed to some degree; techniques employed in the heating study are specifically described here.

The general procedure consisted of operating the collector on cloudy as well as sunny days in order that measured heat recoveries would be representative of those which would be obtained during a normal operating season. During a day's run of the collector, measurements of the air temperatures at the inlets and outlets of all four rows were continuously recorded. The air flow rate was held constant and identical in each of the four rows, as indicated by the rotameters. Solar intensities on the phyrheliometer, positioned at an angle of 27° facing south, were continuously recorded.

Operation of the collector during any one run consisted of starting the circulating blower in the morning as soon as the temperature of the air leaving the collector could be as high as approximately 80° F. The gate valves at the inlet to each row were then adjusted to a predetermined air rate. As soon as the entrance air temperature rose to 65° F, cooling water was run through the two heat exchangers and the water rate adjusted so that the air entering the collector would remain at 65° F. (the temperature at which air would ordinarily be recirculated from a home to the collector in winter operation).

By dependent variation of air flow rate and inlet air temperature, the experimental results could be employed in correlations of heat recovery and exit air temperatures as affected by solar input rate, air rate, cover plate arrangement, inlet air temperature, ambient air temperature, time of day, and reflectivity of glass. Experimental data were obtained at air flow rates of 0.40, 0.76, 1.12, 1.43, and 1.82 standard CFM per square foot of collector area. Mean daily ambient air temperatures varied from 0° to 65° F while the total daily solar radiation varied from 400 to 2,800 BTU/sq. ft. of collector area.

DISCUSSION OF RESULTS

In figure 3, typical results of performance in a single day's operation of two rows of the collector are shown. Outlet and inlet air temperatures, heat recovery, and solar radiation are plotted against time of day. These data were secured on April 16, 1951, a clear day, at a mean ambient air temperature of 44° F and an air rate of 1.12 standard cu. ft. (measured at 760 mm pressure and 70° F) /min./sq. ft. of collector area. The average inlet air temperature was maintained at approximately 65° F. The useful heat recovered was considered as the heat recovered above 70° F whenever the outlet air temperature from the collector was at least 80° F, the minimum temperature at which heat could in all probability be economically recovered. Barometric pressure in the collector was approximately 630 mm.

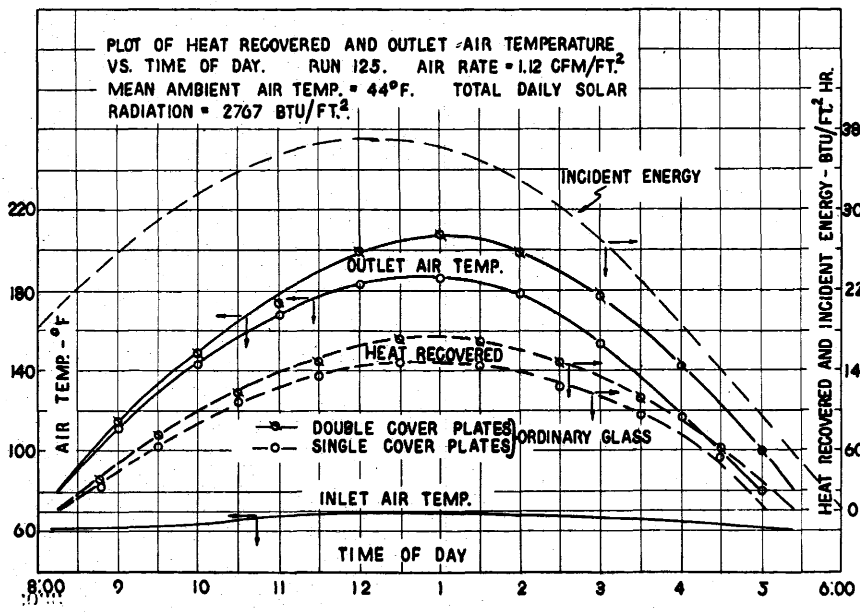

FIGURE 3. Plot of heat recovered and outlet air temperature vs. time of day. Run 125. Air rate = 1.12 cfm/ft². Mean Ambient air temp. 44° F. Total daily solar radiation = 2767 BTU/ft.²

It is seen from the curves that the exit temperature and heat recovery both increase from comparatively low values in the early morning to maximum values at approximately 1:00 P.M. and then decrease to low levels in the late afternoon. The temperature and heat recovery curves do not reach a maximum at noon as does the solar radiation because of sensible heat storage in the glass and other components of the collector. The rather wide variation of temperature and heat recovery are of course due to the change in solar intensity throughout the day; if desired, the temperature variation could be reduced by adjusting the air rate from time to rime rather than holding it constant. Heat recovery efficiency may be visualized by noting that the area under each heat recovery curve divided by the total area under the solar radiation curve is equal to the efficiency.

In figure 4 are shown the performance characteristics of a row provided with ordinary glass and single cover plates when operated at an air flow rate of 1.12 CFM/sq. ft. of collector area. Useful heat recovered is plotted against total daily incident radiation, with ambient air temperature as parameter. Each point on the plot represents a single day's run; ambient air temperature was the Weather Bureau mean for the 24-hour period beginning at 12:00 mid-night. The lines through the data points indicate that heat recovery rises nearly linearly with an increase in incident solar radiation. It can easily be shown that the efficiency, i.e., heat recovered divided by the total incident energy, is not constant, but varies both with total daily incident energy and ambient air temperature.

From theoretical consideration, it is evident that the mean ambient air temperature is a suitable parameter in the correlation of heat recovery. Since the solar collector is exposed to the atmosphere, during the night the temparature of the materials in the collector will approach the ambient air temparature, or on clear nights may drop below air temparature because of radiation to the sky; on a day following a cold night considerable solar radiation will be required to heat the

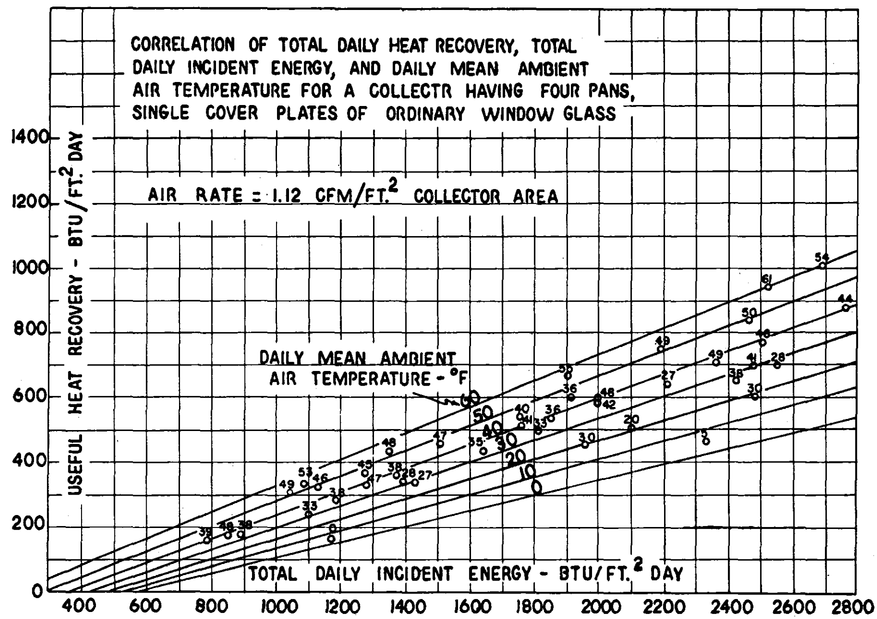

FIGURE 4. Correlation of total daily heat recovery, total daily incident energy, and daily mean ambient air temperature for a collector having four pans, single cover plates of ordinary window glass.

glass in the collector to a temperature at which useful heat may be recovered. Also, on a day of low ambient air temperature, the radiation and conduction loss from the collector during daylight operation will be larger than during warm weather. Conversely, on a warm day following a warm night, the sensible heat lag of the collector and the radiation and conduction losses will be smaller so that more useful heat may be collected per unit quantity of solar radiation. As can be seen in figure 4, the radiation and conduction losses during the day and the sensible heat lag resulting from the previous night's ambient air temperature are such that for a particular total daily solar radiation and air rate, the useful heat recovered rises nearly linearly with mean ambient air temperature.

As seen in figure 4, the experimental points generally show deviations from the mean within approximately 5 percent. In all cases of larger inconsistency, the deviations may be attributed to any one or several of the following factors;

(1) The mean ambient air temperatures (the mean of the high and low temperattures for a 24-hour period beginning at 12:00 mid-night) as given by Weather

Bureau records do not represent the mean temperature during the day and previous night. An example might be a 24-hour period in which the ambient air temperature was high for the day and the previous night, but was abnormally low during the early evening following the day's collector operation.

(2) A low overcast sky in which case the radiation loss from the collector cover plates will be lower than during a clear day.

(3) Abnormally high winds causing large conduction losses. However, even with these variations, the data show a maximum deviation of approximately 10 percent.

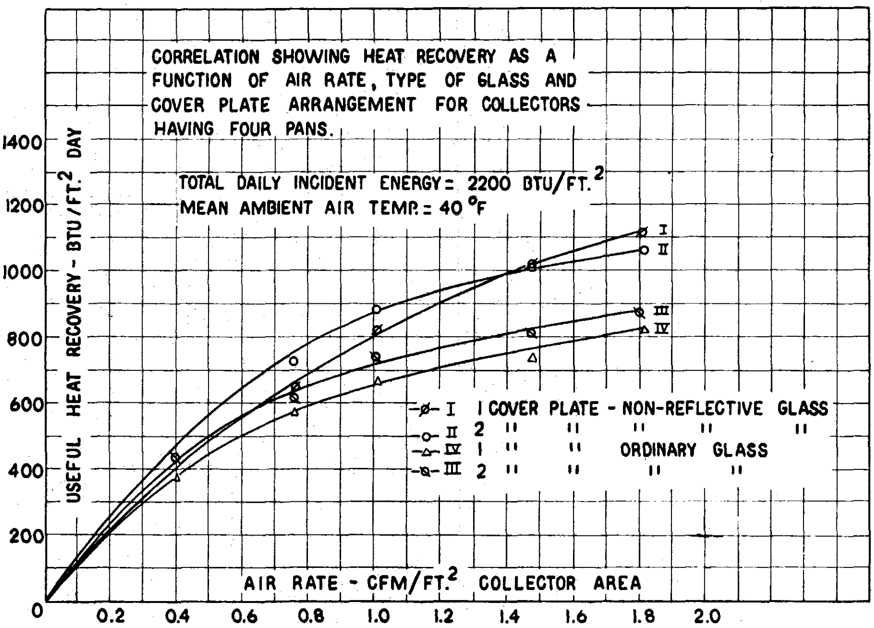

FIGURE 5. Correlation showing heat recovery as a function of air rate, type of glass and cover plate arrangement for collectors having four pans.

The relationship between useful heat recovery, air flow rate, cover plate arrangement, and ordinary and non-reflective glass for a total daily solar radiation of 2,200 BTU/sq. ft. and a mean ambient air temperature of 40° F. is shown in figure 5. It is seen that useful heat recovery rises as air circulation rate is increased and that there is a considerable difference in the performance of collector rows having different cover plate arrangement and ordinary or non-reflective glass. The fact that heat recovery increases with air circulation rate, results from the lower exit air temperatures and glass temperatures and corresponding reduction in heat loss from the cooler collector unit. As seen in figure 5, the heat recovery at a given air rate is considerably greater for collectors provided with non-reflective glass than collectors having ordinary glass. This difference may be attributed to the higher transmittance of the non-reflective glass.

It is noted that the heat recovery for a row having single cover plates and non-reflective glass (Curve I) is higher than the heat recovery for a row having double covers and non-reflective glass (Curve II) at air rates greater than 1.5 CFM/sq. ft. of collector and that at air rates below this value the recoveries are reversed. This may be explained by consideration of the relative magnitude of the radiation and the reflection losses from the collector. At low air rates, at which high cover plate temperatures prevail, the reflection loss for double covers is small relative to large radiation losses from single cover plates. At high air rates and correspondingly lower cover plate temperatures, the reverse is true.

It is observed that the heat recovery for a row having single cover plates and ordinary glass (Curve IV) is lower than the heat recovery for a row having double covers and ordinary glass (Curve III) over the entire range of air rates shown. Again, this may be explained by consideration of the relative magnitude of the radiation and reflection losses from the collector. In contrast to the relatively low reflection losses of non-reflective glass, the ordinary glass exhibits relatively high losses compared to the radiation and conduction losses over the range of air rates shown.

Although final choice of cover plate arrangement and type of glass used in the collector will depend upon the result of an economic balance, it is thought that the probable desirable type of arrangement will be with the use of single cover plates and non-reflective glass. With this cover plate arrangement, and at an air rate of 1.5 CFM/sq. ft. of collector area, which is in the approximate range of operation that would probably be used for commercial operation, heat recovery on a clear day at a mean ambient air temperature of 40° F would be about 50 percent of the total daily incident energy.

It is estimated that the maximum error in determination of the total daily incident energy is ± 2 percent. Calibration of the thermocouples used for all temperature measurements indicated a maximum error of ± 2° F. The four Flowrators used for air flow measurements were calibrated with a positive displacement gas meter which indicated a maximum percentage error of 4 percent at the lowest air rates employed. It is estimated that the heat recoveries deviate not more than 5 percent from their true values.

CONCLUSIONS

Studies of the performance of a solar energy collector of the overlapped glass plate type have resulted in the following conclusions:

(1) A solar energy collector unit has been developed which should be produceable on a factory basis, and suitable for installation in a new dwelling without extensive fabrication at the site.

(2) At a particular air rate and total daily solar radiation, the useful heat recovered increases approximately linearly with the mean ambient air temperature.

(3) At a particular air rate and mean ambient air temperature, heat recovery increases linearly with an increase in total daily solar radiation.

(4) At a particular total daily solar radiation and mean ambient air temperature, the heat recovery increases with air rate.

(5) The heat recovery for a row provided with single cover plates and non-reflective glass is higher than the heat recovery for a row provided with double covers and non-reflective glass at air rates greater than 1.5 CFM/sq. ft. of collector; at air rates below the value the recoveries are reversed.

(6) The heat recovery for a row having double cover plates of ordinary glass is greater than a row having single cover plates over the range of air rates studied.

(7) The heat recovery of a row having non-reflective glass is appreciably greater than a row having ordinary glass.

(8) With a collector as designed, heated air ranging in average temperature from 120° to 180° F. at heat recovery efficiencies in the vicinity of 50 percent can be delivered to a dwelling on sunny winter days at 40° latitude.

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